Music 270a:
Fundamentals of Audio, Acoustics and Sound

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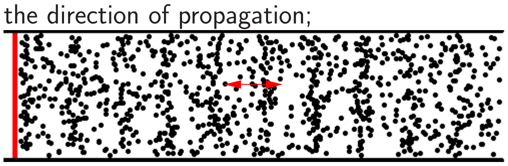
Sound

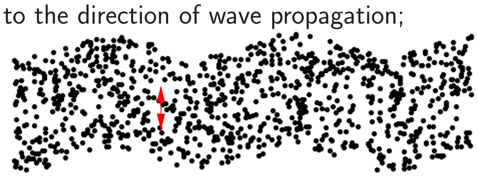
- Sound is the result of a **wave** created by vibrating objects, propagated through a medium from one location to another.
- Sound is thus a **mechanical** wave:
  - a disturbance travelling through a medium;
  - transports energy from one location to another;
- When synthesizing sound, we may synthesize:
  1. the waveform generated by a vibrating system (signal-based modeling)
  2. the vibrating system itself (acoustic modeling)

Sound Waves

- In particular, sound is the result of **travelling waves**:
  - waves propagating in one direction with negligible change in shape;
  - *longitudinal*: particle displacement is parallel to the direction of propagation;

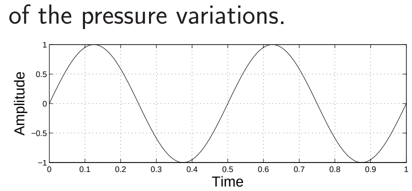


  - *transverse*: particle displacement is perpendicular to the direction of wave propagation;



Sound Waveform

- Sound waves are *longitudinal* waves: a disturbance (source) creates an initial region of compression or high pressure.
- When the source vibrates, alternating regions of low and high pressure, *rarefactions* and *compressions*, are produced.
- The *waveform* of the sound shows the time evolution of the pressure variations.



- **Properties of a Wave**:
  - **Amplitude**: maximum particle displacement from rest (Pa or N/m^2).
  - **Wavelength**: length of one complete cylce (m).
  - **Period**: time to complete one cycle (s).
  - **Frequency**: number of cycles per second (Hz).

Properties of Sound Waves

- Speed of sound[1]:
  - in air: 340 m/s
  - in water: 1480 m/s
- Amplitude range of hearing (humans)
  - Threshold of audibility: 0.00002 N/m^2
  - Threshold of feeling (or pain!): 200 N/m^2
- Frequency range of hearing
  - humans: 20 - 20 000 Hz
  - dogs: 20 - 45 000 Hz
  - beluga whale: 1000 - 123 000 Hz
- Period of lowest and highest audible frequencies
  - 1/20 Hz = 0.05 s   1/20 000 Hz = 0.05 ms
- Shortest audible wave
  - 340/20000=1.7cm
- Longest audible wave
  - 340/20=17m

[1] Quantity depends on temperature: For air, the speed of sound is $c = 20.1\sqrt{(T)}$, where T is the absolute temperature found by adding 273 to the temperature on the Celsius scale.

Power and Intensity

- Waves can represent a number of time-evolving physical variables (force, velocity, acceleration, etc.).
- For *sound* waves, the physical variable represented by the amplitude of the waveform is pressure.
- Related to the sound pressure are
  1. the sound **power** emitted by the source
  2. the sound **intensity** measured some distance from the source.
- **Sound power**:
  - a **fixed** quantity, analogous to the wattage rating of a light bulb.
- **Sound intensity**:
  - a **quantity influenced** by environment surroundings, surfaces, and interference from other sources
  - analogous to the brightness of the light in a particular part of the room

Intensity

- **Intensity** is
  - the power **per unit area** carried by the wave,
  - measured in watts per square meter (W/m^2).
- **Sound intensity** is
  - a measure of the sound power that contacts an area (e.g. eardrum, microphone).
- Sound is audible to humans when its intensity is above

$$I_0 = 10^{-12} \text{ W/m}^2,$$

  with 1 W/m^2 being the *threshold of feeling*.
- Intensity is related to pressure squared:

$$I = p^2/(\rho c),$$

  where
  - p is the pressure,
  - ρ is the density of air (kg/m^3), and
  - c is the speed of sound (m/s).

Linear vs. logarithmic scales.

- Human hearing is better measured on a logarithmic scale than a linear scale.
- On a *linear* scale, a change between two values is perceived on the basis of the **difference** between the values:
  - e.g., a change from 1 to 2 would be perceived as the same increase as from 4 to 5.
- On a *logarithmic* scale, a change between two values is perceived on the basis of the **ratio** of the two values:
  - e.g., a change from 1 to 2 would be perceived as the same increase as a change from 4 to 8.

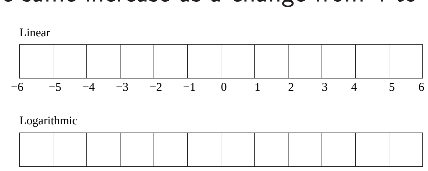


Figure 1: Moving one unit to the right increment by 1 on the linear scale and multiplies by a factor of 10 on the logarithmic scale.

Decibels

- The decibel (dB) is a unit named after Alexander Graham Bell, known as a telecommunications pioneer.
- A decibel is defined as one tenth of a bel, i.e., to convert from Bel to dB you multiply by 10:

$$1 \text{ B} = 10 \text{ dB}$$

- The decibel is a logarithmic scale, used to compare two quantities such as the power gain of an amplifier or the relative power of two sound sources.
- The decibel difference between two power levels ΔL for example, is defined in terms of their power ratio W_2/W_1 and is given in decibels by:

$$\Delta L = 10 \log W_2/W_1 \quad \text{dB}.$$

- Since power is proportional to intensity, the ratio of two signals with intensities I_1 and I_2 is similarly given in decibels by

$$\Delta L = 10 \log I_2/I_1 \quad \text{dB}.$$

Sound Power and Intensity Level

- Decibels are often used as absolute measurements, with one of the quantities being a fixed reference.
- The *sound power level*

$$L_W = 10 \log W/W_0 \text{ dB},$$

and *sound intensity level*

$$L_I = 10 \log I/I_0 \text{ dB},$$

of a source, may be expressed using the threshold of audibility as a reference, defined by

$$\begin{aligned} W_0 &= 10^{-12} \text{ W}, \\ I_0 &= 10^{-12} \text{ W/m}^2. \end{aligned}$$

Sound pressure Level

- Recall that intensity is proportional to sound pressure amplitude squared:

$$I = p^2/(\rho c).$$

- Though ρ and c are dependent on temperature, their product is often approximated by 400.
- When $\rho c = 400$, **sound pressure level L_p (SPL) is equivalent to sound intensity level**, and is expressed in dB by:

$$\begin{aligned} L_p &= 10 \log I/I_0 \\ &= 10 \log p^2/(\rho c I_0) \\ &= 10 \log p^2/(4 \times 10^{-10}) \\ &= 10 \log \left(p/(2 \times 10^{-5})\right)^2 \\ &= 20 \log p/(2 \times 10^{-5}) \\ &= 20 \log p/p_0. \end{aligned}$$

where $p_0 = 2 \times 10^{-5}$ is the threshold of hearing for amplitude of pressure variations.

Increasing distance from a source

- A *point source* is one that radiates equally in all direction.
- When it radiates into *free space*,
  - **the intensity decreases by** $1/r^2$ (as the radius r of a sphere increases, its surface area expands by $(4\pi r^2)$, and
  - **the pressure decreases by** $1/r$ (this follows from intensity being proportional to pressure squared),

  where r is the distance from the source.
- In actual practice, sound sources wouldn't radiate so symmetrically as there would interference from other reflective objects.

Sound level when doubling the distance

- So how does the sound intensity level change with a doubling of distance?
- We know that the intensity will drop by $1/2^2$ and thus

$$\begin{aligned} L_I &= 10\log(1/2^2 \times I/I_0) \\ &= 10\log(I/I_0) + 10\log(1/2^2) \\ &= 10\log(I/I_0) + 10\log(2^{-2}) \\ &= 10\log(I/I_0) - 20\log(2) \\ &= 10\log(I/I_0) - 20(.3) \\ &= 10\log(I/I_0) - 6 \text{ dB}. \end{aligned}$$

- Doubling the distance from a source causes a **decrease** of 6dB in the sound level.

Multiple sound sources

- When there are multiple *uncorrelated* sound sources, the total power emitted is the *sum* of the power from each source.
- Question: By how much would the sound level increase when two (uncorrelated) sources sound simultaneously with equal power?
- Solution: The sound power (at the source) would double and thus,

$$\begin{aligned} L_W &= 10\log 10(2W/W_0) \\ &= 10\log 10(W/W_0) + 10\log 10(2) \\ &= 10\log 10(W/W_0) + 3 \text{ dB}, \end{aligned}$$

  there would be an increase of 3 dB in the sound power level.
- Similarly, there would be a 3 dB increase in the sound intensity level measured at some distance away from the source.
- This is the case most of the time. However, there is an exception...

Multiple correlated sound sources

- In rare (or contrived) cases, if the sound sources emit waveforms that are strongly *correlated*, there will be *interference*.
- Solution 2: When two waves of the same frequency and amplitude A reach the same point, they may interfere *destructively* or *constructively* resulting in a pressure amplitude range of
  - 0 (complete *destructive* interference) to
  - $2A$ (complete *constructive* interference).
- In the case of a doubling of pressure, there's an increase of $20\log(2) = 6$ dB.
- Thus doubling the sound source can result in a sound level change of 0-6 dB (depending on interference) for **correlated sounds**.